

# Higher order QCD effects in $WW$ production with jets

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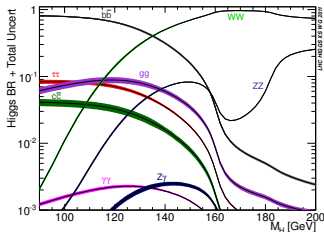
arXiv:hep-ph/1205.6987

Argonne, 22 January 2013

# Outline

- ▶ Motivation
- ▶ Brief outline of generalized unitarity
- ▶  $WWjj$  to NLO in QCD
- ▶ Gluon fusion effects in  $WW$ ,  $WWj$
- ▶ Conclusion

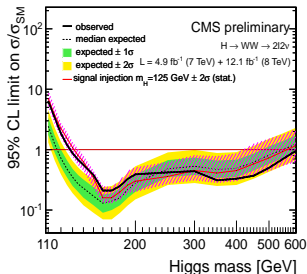
# $H \rightarrow WW$ decay mode



- Evidence of Higgs in this channel ( $3.1 \sigma$ )

## Higgs searches:

- $H \rightarrow WW$  subdominant mode
- Leptonic decay  $\rightarrow$  mass reconstruction not possible

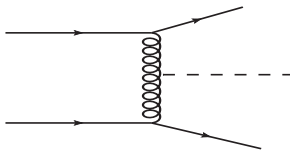
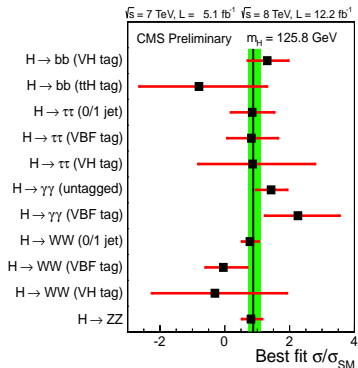


# Electroweak-Higgs coupling

- ▶  $H \rightarrow WW$  probes coupling of Higgs to **EW sector**
- ▶ Tree-level relation between  $W, Z$  mass and coupling to Higgs protected by **custodial symmetry**
- ▶ Rescaling of  $W$ - and  $Z$ -coupling to Higgs parametrized by  $\kappa_W, \kappa_Z$  .
- ▶  $\lambda_{W,Z} = \kappa_W / \kappa_Z = 1$  in SM
- ▶ Current CMS value:  $\lambda_{W,Z} = [0.57, 1.65]$
- ▶ Consistent with SM, but **tighter bounds** desirable

# WW as background to GF and VBF Higgs

- ▶ Higgs signals sorted into 0,1,2+ jet bins  
→ allows identification of backgrounds in each bin
- ▶ Around 30% of Higgs created with one jet, around 15% with two (or more) jets
- ▶  $H(\rightarrow WW)jj$  created through weak boson fusion (WBF) as well as gluon fusion (GF)
- ▶ WBF has characteristic **forward jets** with little hadronic activity between them
- ▶  $WW(+ \text{ jets})$  is irreducible background to all processes



## $WW$ production as signal

$WW$  production also interesting in its own right, or as place where New Physics may be found (e.g. in trilinear vector boson couplings)

- ▶ Recent CMS result for  $WW$  production finds  $\sigma = 69.9 \pm 2.8 \pm 5.6 \pm 3.1$  pb
- ▶ Prediction:  $\sigma = 57.7^{+2.4}_{-1.6}$  pb
- ▶  $2\sigma$  effect ...

# Why NLO?

- ▶ Comparisons with Tevatron data show LO is **insufficient** - NLO needed
- ▶ NLO corrections can be large ( $\sim 60\%$  enhancement for  $WW$  production)
- ▶ No guarantee that this enhancement will be consistent over phase space or distribution
- ▶ Factorization/renormalization scale uncertainty **significantly reduced** at NLO

# How NLO?

Three ingredients needed for NLO calculations:

- ▶ Real emission correction
- ▶ Virtual (one-loop) amplitudes → generalized unitarity/OPP procedure
- ▶ Matching of IR divergences in real emission corrections to those in virtual amplitudes → Catani-Seymour dipoles

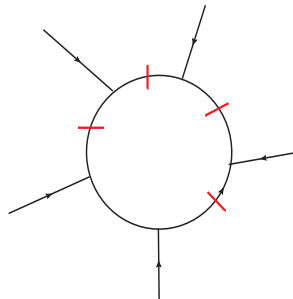


# Generalized Unitarity method

- ▶ Virtual amplitudes stripped of color factors to give **partial amplitudes** → **primitive amplitudes**
- ▶ OPP subtraction: tensor integrals in primitive amplitudes written in terms of **scalar integrals** (known) and **coefficients**
- ▶ Analytic form of coefficients known
- ▶ By choosing (complex) momenta such that propagators vanish, can solve for coefficients

# Generalized Unitarity method

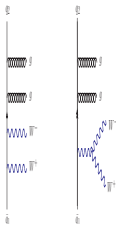
- ▶ Equivalent to performing a **unitarity cut** on the primitive amplitudes, resulting in tree-level helicity amplitudes
- ▶ → computed with **Berends-Giele currents** (also used to calculate Born amplitudes and real emission corrections)



# $WWjj$ production

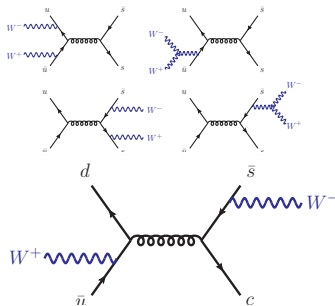
Two distinct **strong** production processes:

Two quark, two gluon processes:



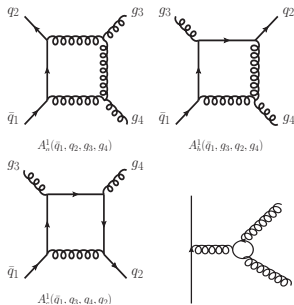
All permutations of  $W$ -bosons with gluons

Four quark processes:

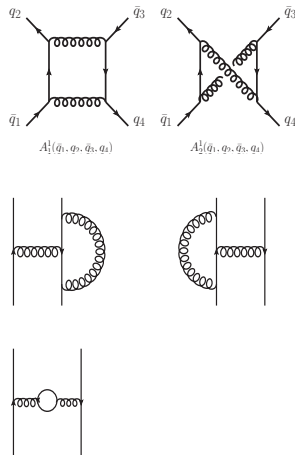


Also  $t$ -channel contributions  $\rightarrow$   
Complicated flavor structure

**Four** primitive amplitudes for **2q,2g** process:



**Five** primitive amplitudes **4q** process:

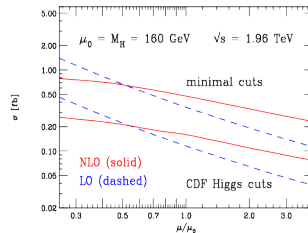
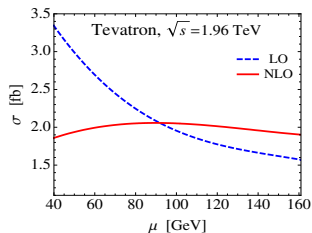


**Signature:** two opposite-sign leptons, missing energy, two or more jets

Cuts used similar to CDF in Higgs searches:

- ▶ Jets defined using  $k_T$ -algorithm with  $\Delta R_{j1j2} > 0.4$
- ▶ Jet cuts:  $p_{T,j} > 15$  GeV and  $|\eta_j| < 2.5$
- ▶ Lepton cuts:  $p_{T,l1} > 20$  GeV,  $|\eta_{l1}| < 0.8$ ;  $p_{T,l2} > 10$  GeV,  $|\eta_{l2}| < 1.1$
- ▶ Lepton isolation: jets within  $\Delta R = 0.4$  of a lepton must have  $p_{T,j} < 0.1 p_{T,l}$ .
- ▶ Lepton cuts:  $m_{ll} > 16$  GeV and  $p_{T,\text{miss}}^{\text{spec}} \equiv p_{T,\text{miss}} \sin[\min(\Delta\phi, \pi/2)] > 25$  GeV

# Tevatron Results



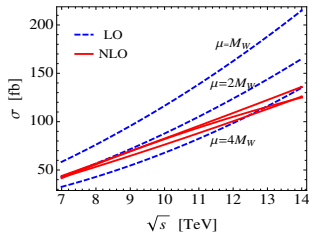
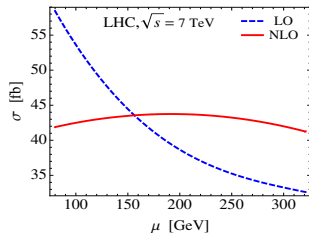
From Campbell, Ellis, Williams, hep-ph:1001.4495

- ▶  $\sigma_{LO} = 2.5 \pm 0.9$  fb,  $\sigma_{NLO} = 2.0 \pm 0.1$  fb
- ▶ At LO, **uncertainty** in background four times larger than **signal**!
- ▶ Uncertainty reduced at NLO by order of magnitude, but still **comparable** to signal.

Look at  $WWjj$  as **signal**:

- ▶ Center-of-mass energy  $\sqrt{s} = 7$  TeV
- ▶ Jets defined with anti- $k_t$  algorithm with  $\Delta R_{jj} = 0.4$
- ▶ Jets cuts:  $p_{T,j} > 30$  GeV and  $|\eta_j| < 3.2$
- ▶ Lepton cuts:  $p_{T,l} > 20$  GeV,  $|\eta_l| < 2.4$ ,  $p_{T,\text{miss}} > 30$  GeV

# LHC cross-sections



- ▶  $\sigma_{LO} = 46 \pm 13$  fb,  $\sigma_{NLO} = 42 \pm 1$  fb
- ▶ At NLO, **approximately linear** increase in cross-section as  $\sqrt{s}$  increased
- ▶ “Optimal” factorization/renormalization scale:  $2m_W$  at  $\sqrt{s} = 7$  TeV,  $4m_W$  at  $\sqrt{s} = 14$  TeV

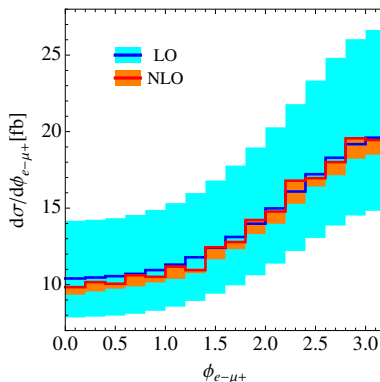


# LHC angular distribution

To discriminate between signal and background: **distributions**

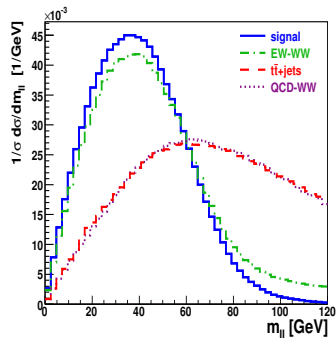
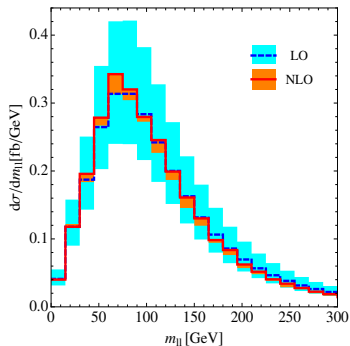
Useful distribution: **opening angles between leptons**  $\phi_{e^-\mu^+}$ .

Higgs: **small angle**; background: **back-to-back**



# LHC mass distribution

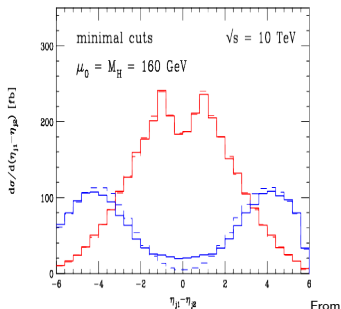
Linked to  $\phi_{e-\mu^+}$  is mass of lepton system  $m_{ll}$



From Klämke and Zeppenfeld, hep-ph:0703202

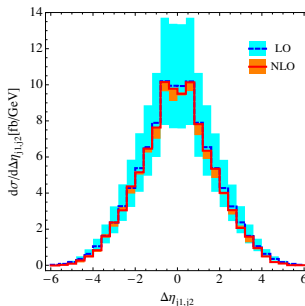
# Today's signal is tomorrow's background

Higgs created through **GF** has central jets;  
through **VBF** has forward jets



Campbell, Ellis, Williams, hep-ph:1001.4495

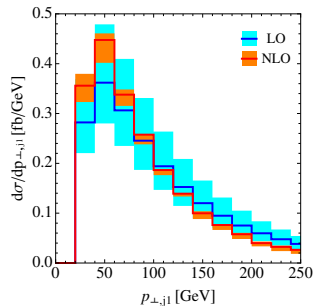
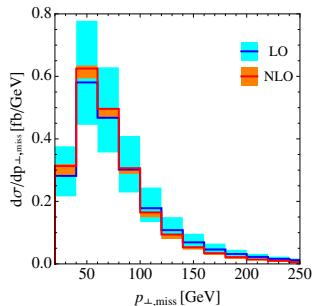
Background jets **central**



Cut on central jets removes both  $WWjj$  and GF background

NLO results **greatly reduce scale uncertainty** → improved reliability

# LHC distributions



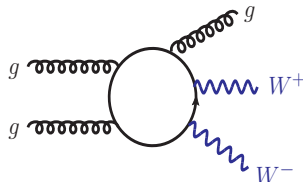
- ▶ Mild softening at high scales - indication that fixed scale is too small, and **dynamic scale** would be better
- ▶ Reduced scale uncertainty again apparent

# Gluon fusion in $WW$ production

$WW + n$  jets with no external quarks  
- only gluons - through a fermion loop

No corresponding tree-level amplitude:

- ▶ One-loop amplitude is finite
- ▶ Enters as a NNLO correction to  $pp \rightarrow WW + n$  jets



Finite, gauge invariant, self-contained contribution to NNLO correction.

Additional factors of  $\alpha_s \leftrightarrow$  Large gluon flux at LHC

# Gluon-induced $WW$ production

$gg \rightarrow WW$  studied by Binoth, Ciccolini, Kauer, Krämer

hep-ph:0503094, hep-ph:0611170

Find highly **cut-dependent** contribution to overall cross-section:

- ▶ For generic cuts\*,  $\sigma_{gg+NLO}/\sigma_{NLO} = 1.06$
- ▶ For Higgs search cuts\*\*,  $\sigma_{gg+NLO}/\sigma_{NLO} = 1.30$

\*  $p_{T,l} > 20 \text{ GeV}$ ,  $|\eta_l| < 2.5$ ,  $p_{T,\text{miss}} > 25 \text{ GeV}$

\*\*  $35 \text{ GeV} < p_{T,l\text{max}} < 50 \text{ GeV}$ ,  $p_{T,l\text{min}} > 25 \text{ GeV}$ ,  $\Delta\phi_{ll} < 0.78$ ,  $m_{ll} < 35 \text{ GeV}$ ,  
 $p_{T,j} > 20 \text{ GeV}$ ,  $|\eta_j| < 3$

BUT these cuts are not what LHC uses:

- ▶ Initially proposed:  $\Delta\phi_{ll} < 1.8$ ,  $m_{ll} < 50 \text{ GeV}$  ATLAS-CONF-2012-012
- ▶ End 2012 analysis:  $\Delta\phi_{ll} < 0.87$ ,  $m_{ll} < 43 \text{ GeV}$  ( $m_H$  dependent cuts)

## Standard cuts

Looked at  $gg \rightarrow WW$  and  $gg \rightarrow WWj$ :

### Standard Cuts

		$\sigma_{\text{LO}}$ (fb)	$\sigma_{\text{NLO}}^{\text{incl}}$ (fb)	$\delta\sigma_{\text{NNLO}}$ (fb)	$\delta\sigma_{\text{NNLO}}/\sigma_{\text{NLO}}^{\text{incl}}$
8 TeV	$WW$	$141.0(1)^{+2.8}_{-4.0}$	$232.0(4)^{-5.8}_{+7.5}$	$8.1(1)^{-1.7}_{+2.2}$	3.5%
	$WWj$	$87.8(1)^{-10.9}_{+13.5}$	$111.3(2)^{-5.5}_{+4.9}$	$3.4(1)^{-1.0}_{+1.6}$	3.1%
14 TeV	$WW$	$259.6(2)^{+14.2}_{-17.2}$	$448.3(5)^{-7.4}_{+11.6}$	$23.6(1)^{-4.1}_{+5.2}$	5.3%
	$WWj$	$203.4(1)^{-19.9}_{+22.9}$	$254.5(4)^{-10.2}_{+9.0}$	$11.8(4)^{-3.2}_{+4.7}$	4.6%

- ▶ For  $WW$  production, results similar to Binoth *et al.*
- ▶ Gluon-induced production **more important** at  $\sqrt{s} = 14$  TeV
- ▶ Gluon-induced production **less important** for  $WWj$  production

## Higgs search cuts

		$\sigma_{\text{LO}}$ (fb)	$\sigma_{\text{NNLO}}^{\text{excl}}$ (fb)	$\delta\sigma_{\text{NNLO}}$ (fb)	$\delta\sigma_{\text{NNLO}}/\sigma_{\text{NNLO}}^{\text{excl}}$
8 TeV	WW	$35.6(1)^{+0.9}_{-1.3}$	$38.8(1)^{+1.0}_{-0.8}$	$2.7(1)^{-0.5}_{+0.7}$	7.0%
	WWj	$12.6(1)^{-1.5}_{+1.8}$	$10.6(1)^{+0.3}_{-0.9}$	$0.6(1)^{-0.2}_{+0.2}$	5.7%
14 TeV	WW	$63.4(1)^{+3.9}_{-4.7}$	$63.4(2)^{+2.1}_{-2.0}$	$7.5(1)^{-1.2}_{+1.5}$	11.8%
	WWj	$28.7(1)^{-2.6}_{+2.9}$	$20.5(1)^{+1.7}_{-2.2}$	$1.8(2)^{-0.5}_{+0.7}$	8.8%

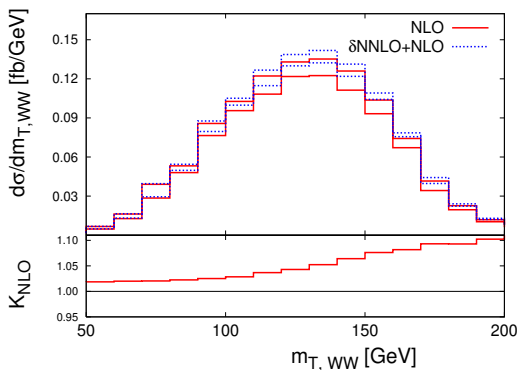
- Important contribution to overall cross-section (comparable to **NLO scale uncertainty**)
- **BUT** not as large as 30% contribution
- *Hj* production:  $\sigma \approx 2$  fb at  $\sqrt{s} = 8$  TeV, 5 fb at  $\sqrt{s} = 14$  TeV  
→ **gluon-induced NNLO contribution** to background **third** of signal cross-section



# NNLO $K$ -factor

Define

$$K_{NLO} = \frac{d\sigma_{NLO+\delta NNLO}}{d\sigma_{NLO}}$$



$K$ -factor is **not uniform** over phase space and its distribution can be **cut-dependent**

# Conclusions

- ▶ NLO QCD corrections to strong production of  $WWjj$  computed.
- ▶ **Moderate** (10-20%) change in cross-section compared to LO, but scale uncertainty reduced by up to **order of magnitude**.
- ▶ Improves reliability of distributions aiding discrimination between Higgs signal and  $WW$  background:  $\phi_{ll}$ ,  $m_{ll}$ ,  $\Delta\eta_{jj}$   
→ allow **discovery** in this channel; study Higgs-EW couplings
- ▶ NNLO gluon-induced corrections to  $WW$  and  $WWj$  production computed
- ▶ These are **cut-dependent**, more important as cuts become more aggressive
- ▶ May be as large as NLO scale uncertainty, and factor 2-3 smaller than signal